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The extant shore platform stromatolite (SPS) facies association: a glimpse into the Archean?

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Abstract. Shore platform stromatolites (SPS) were first noted at Cape Morgan on the south-east African seaboard. Since then they have been found growing discontinuously in rocky peritidal zones along the entire southern African seaboard. They have also been found on the southwest Australian coast, at Giant's Causeway in Northern Ireland, and more recently at Harris on the Scottish Hebridean Atlantic coast. In this paper SPS occurrence and SPS potential as analogues for Precambrian fossil stromatolites, as well as potential stromatolite occurrences in shore platform regions on Mars, are assessed. Sub-horizontal surfaces promote stromatolite development, while tufa develops on cliffs and steep rocky surfaces. Tufa and stromatolites are end members of a spectrum dictated by coastal topography. Extant SPS occur on well indurated shore platforms in high wave energy settings, often around or near headlands. They can be associated with boulder beaches, boulder ridges, storm swash terraces, coastal dunes, and peat bogs. In contrast to other extant stromatolites, SPS are produced primarily by mineral precipitation, although minor trapping and binding stromatolites do occur. From a geological perspective, SPS develop in mildly transgressive siliciclastic settings in various climatic and tidal regimes. We suggest that SPS could be preserved in the geological record as micritic lenses on palaeo-shore platform surfaces. SPS share many features with Precambrian stromatolites and are a valid modern analogue despite the widely different atmospheric and oceanic conditions of

the Archean. We suggest that terraces associated with former oceanic or lacustrine flooding surfaces on Mars are potential targets in the search for palaeo-SPS on Mars.

1 Introduction

The oldest known stromatolites include those of the Isua Group (3.7 Ga), Greenland (Nutman et al., 2016); the Strelley Pool occurrence (3.43 Ga), Australia (Allwood et al., 2006); the Barberton Mountain Land (3.22 Ga), South Africa (Gamper et al., 2011); and the Pongola Group (2.9 Ga), South Africa (Mason and von Bruun, 1977; Bolhar et al., 2015). Comparison of the environment in which extant and sub-fossil stromatolites occur with ancient examples may advance our knowledge concerning the conditions under which life developed and in what environment it began. Stromatolite-building organisms probably dominated the Earth during the Archean and Proterozoic eons, but under contemporary conditions only thrive in extreme environments that limit metazoan competition. Such environments include geothermal springs (Jones et al., 2000; Berelson et al., 2011), peritidal marine environments (Logan et al., 1964; Reid et al., 2000; Smith and Uken, 2003; Smith et al., 2005, 2011; Perissinotto et al., 2014; Rishworth et al. 2016; Edwards et al., 2017), and salt lakes (Martin and Wilczewski, 1972). Prokaryotes are also recorded from the Earth's upper

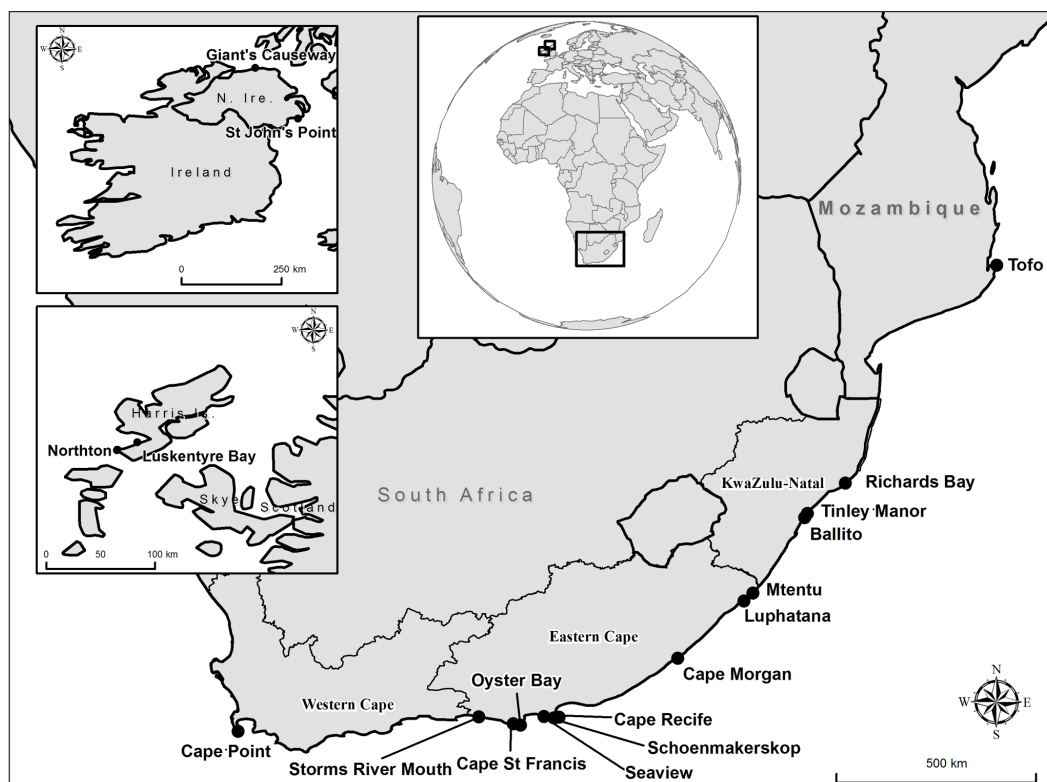


Figure 1. Location of SPS sites on the eastern seaboard of southern Africa, Northern Ireland and the Scottish Hebrides.

crust to depths of (at least) 7 km (Sankaran, 1997) and within the troposphere (DeLeon-Rodriguez et al., 2012).

Stromatolites are biosedimentary structures produced by sediment trapping and binding and/or mineral precipitation as a result of the growth and metabolic activity of a microbial community (Awramik and Margulis, 1976; Burne and Moore, 1987). The best known extant stromatolite models are based on the trapped and bound stromatolites of Shark Bay, Western Australia and several sites in the Caribbean (Logan et al., 1964; Reid and Browne, 1991). Precambrian stromatolites, in contrast, are of the mineral precipitation variety (Awramik and Grey, 2005; Reid et al., 2011; Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016; Edwards et al., 2017) and offer a plausible Precambrian stromatolite analog, which deserves scrutiny.

Cape Morgan (Fig. 1) in the Eastern Cape province, South Africa, was the first location where SPS were found. SPS form on shore platforms within the peritidal zone where suitable (carbonate-rich) terrestrial runoff is present (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016). These supratidal/ high intertidal zones experience extreme environmental changes, which partially exclude metazoans (Perissinotto et al., 2014; Rishworth et al., 2016) and enable prokaryotes to dominate. The Cape Morgan locality was discovered by Mountain (1937), although its significance was only realised much later (Smith and Uken, 2003). Smith et

al. (2011) proposed the extant Cape Morgan (Fig. 1) stromatolites as a partial analogue for the 3.43 Ga stromatolites from Strelley Pool Australia. Smith et al. (2011) furthermore documented extant and subfossil SPS from Cape Morgan and indicated that they were found in patches from Tofo (Mozambique) to Port Elizabeth (Eastern Cape, South Africa) (Fig. 1). Since then colonies have been found in Northern Ireland (Cooper et al., 2013), additional localities in the Eastern Cape province have been documented, (Perissinotto et al., 2014; Rishworth et al., 2016; Edwards et al., 2017), and further colonies elsewhere in southern Africa have been uncovered (Fig. 1). More recently, new SPS discoveries have also been made on the west coast of Harris, in the Scottish Hebrides.

2 Methodology

This work is heavily reliant on fieldwork which has taken advantage of many serendipitous trips. No attempt has been made to institute a scientific survey due to the geographical distances involved and limited manpower. Stromatolite (SPS in this paper) morphology, microstructure, and ecology is discussed in detail elsewhere (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016, 2017; Edwards et al., 2017). New localities are discussed and compared with known; such review is required to establish similarities and differences. This paper will consequently focus

Table 1. Location, context and stromatolite type of SPS localities (Y: yes; N: no; n/r: no record).

Location	Coordinates	Shore platform	Cliff	Trapped and bound	Mineral precipitation	Tufa
Cape Point, SA	34°20'48.42" S;	Y	Y			Y
¹ Storms River	18°27'48.16" E 34°10'34" S; 24°39'46" E	Y	n/r	N	Y	n/r
¹ Oyster Bay	34°11'25.07" S;	Y		N	Y	n/r
¹ Cape St Francis	24°41'43.76" E 34°12'49" S; 24°50'04" E	Y	N	N	Y	n/r
¹ Seaview	34°_01'03.16" S;	Y	N	N	Y	n/r
¹ Skoenmakerskop	25°_21'56.48" E 34°_02'28.23" S;	Y	N	Y	Y	n/r
¹ Cape Recife	25°_32'18.60" E 34°_02'42.13" S;	Y	N	N	Y	n/r
² Cape Morgan	25°_34'07.50" E 32°41'36" S ; 28°22'27" E	Y	Minor	Y	Y	Y
Luphatana	31°25'10" S; 29°51'30" E	Y	N	N	Y	N
Mtentu	31°14'30" S ; 31°03'22" E	Y	N	N	Y	N
Port Edward	31°02'55.26" S;	Y	N	N	Y	N
Ballito	30°13' '47.79" E 29°32'15" S;	Y	Minor	N	Y	N
Tinley Manor	31°13'20" E 29°26'43.98" S;	Y	Minor	N	Y	Minor
Richards Bay	31°17'26.99" E 28°46'15.20" S	X	Y	N	Y	Y
Tofo, Mozambique	32°08'00.32" E 23°41'26" S; 35°33'04" E	Y	Y	N	Y	N
³ Giant's Causeway, N. Ireland, UK	See reference	Y	Y	N	Y	N
St John's Point, N. Ireland, UK	54°13'31.23" N;	Y	Y	N	Y	N
Luskentyre Bay (S), Harris, UK	5°39'32.69" W 57°52'08.73" N	Y	Y	N	Y	Y
Luskentyre Bay (N), Harris, UK	6°57'42.01" W 57°52'17.65" N	Y	N	Y	Y	N
Northton, Harris, UK	6°54'28.52" W 57°48'09.56" N	N	Y	N	Y	Y
⁴ Kuwait Bay, Kuwait	7°04'57.52" W See reference	Y	N	N	Y	N
⁵ N. Sea, Netherlands	See reference	N	N	n/r	NA	N
⁶ SW Australia	See reference	Y	Y	N	Y	Y
Monkey Mia, W. Australia	Not known	Y	N	N	Y	N

NA = this data is not available

¹ Perissinotto et al. (2014), ² Smith and Uken (2003), ³ Cooper et al. (2013), ⁴ Alshuaibi et al. (2015), ⁵ Kremer et al. (2008), ⁶ Forbes et al. (2010).

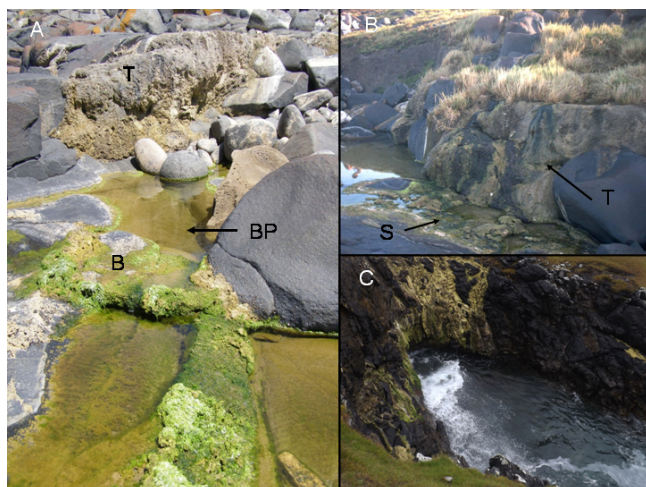


Figure 2. (a) Shore platform showing a low tufa curtain (T), bar-rage (B), and pool (BP). (b) Higher tufa curtain (T) forming on a cliff at the back of the dolerite shore platform with stromatolites (S) at its toe (a and b from Cape Morgan), and (c) Tufa curtain from Northton, Harris, UK. Here there is no shore platform.

on the synthesis of a facies association using tabulated geomorphological, lithological, oceanographic, and climatological elements. This is a relatively new branch of stromatolite science and is heavily reliant on description and comparisons.

We document all known SPS localities (Table 1) with the aim of distilling of a generalised global SPS facies association. To this end we also describe several new SPS localities on the southern African eastern seaboard and on the Atlantic side of Harris Island in the Scottish Hebrides, UK. We then compile and review the physical, oceanographic, climatological, lithological, and geomorphological settings in which extant SPS are forming in the Scottish Hebrides, the northeast coast of Northern Ireland and the southern African seaboard. All known SPS location coordinates and source data are given in Table 1. On the basis of this review, we present a facies association model for SPS.

We then compare the SPS facies association to extant stromatolites from contrasting peritidal environments in Hamelin Pool, Western Australia (Logan et al., 1964), Kuwait (Al-shuaibi et al 2015), the Bahamas (Reid et al., 2000), and the Dutch North Sea (Kremer et al., 2008). Further, on the basis of this comparison, extant SPS are assessed as potential analogues for Precambrian stromatolites. We also comment briefly on potential target location regarding the search for SPS on Mars.



Figure 3. (a) Trapped and bound stromatolites forming on a stromatolite apron, located on the Luskentyre Bay shore platform, Harris, UK. The stromatolite is growing around cobbles swept onto the apron by inflowing water. (b) Trapped and bound stromatolites developed on a cobble beach adjacent to a shore platform. Note the shell debris which has been bound into the Cape Morgan stromatolite. (c) Dolerite boulders quarried from the shore platforms and bound by stromatolite growth. (b) and (c) are reproduced from Smith et al. (2005, 2011).

3 Results

3.1 SPS distribution

Extant shore platform stromatolites (SPS) occur discontinuously along a 2300 km stretch of the southern African eastern seaboard (Fig. 1; Table 1), in addition to locations in Western Australia (Forbes et al., 2010), and Giant's Causeway, Northern Ireland (Cooper et al., 2013). All known SPS occurrences are based on opportunistic observation as no systematic survey of their location has yet been made. SPS often occur in association with tufa but the proportions vary with the coastal geomorphology. All SPS colonies are fed by spring water emanating from the terrestrial hinterland (Smith et al., 2011; Perissinotto et al., 2014; Edwards et al., 2017). If the coastline is cliffed or dominated by high-angle surfaces, tufa dominates (Fig. 2a, b), whereas SPS typically occur within rock pools on competent sub-horizontal shore platforms (Fig. 2a). In many instances there is a clear spatial gradation from tufa to stromatolites (Fig. 2a and b). Most SPS develop directly on the shore platform but the trapped and bound (Fig. 3) variety develops adjacent to, and in channels cut into, the shore platform.

3.2 Trapped and bound SPS

Trapped and bound stromatolites are relatively rare, having only been observed at Cape Morgan (Smith et al., 2011; Fig. 3), Seaview Skoenmakerskop (South Africa: see Ed-

Table 2. Lithological features of shore platforms (N/R: no record).

Location	Lithology	Attitude	Boulders present	Age	Bedrock status
Cape Point, SA	Sandstone (Nardou)	Folded	Boulder beach	Ordovician	very indurated
Storms River	Sandstone (Nardou)	Folded	Boulder ridge	Ordovician	very indurated
Oyster Bay	S/Stone (Nardou)	n/r	n/r	Ordovician	very indurated
St Francis	S/Stone (Nardou)	n/r	n/r	Ordovician	very indurated
Seaview	¹ Quartzites, grits and phyllites	Deformed	Boulders in pools	Precambrian	very indurated
Skoenmakerskop	¹ Metaseds (Sardinia Bay Fm)	Deformed	n/r	Ordovician	very indurated
Cape Recife	S/Stone (Nardou)	Deformed	n/r	Ordovician	very indurated
² Cape Morgan	Dolerite	Sill	Boulder ridge	Jurassic	Fresh
Luphatana	S/Stone (Msikaba)	Horizontally bedded	Boulder ridge	L Devonian	very indurated
Mtentu	S/Stone (Msikaba)	Horizontally bedded	Boulder ridge	L Devonian	very indurated
Port Edward	Granite	Deformed	Boulder ridge	1.1 Ga	Fresh
Ballito	Dolerite	Sill	Storm beach	Jurassic	Fresh
Tinley Manor	Dolerite	Sill	Storm beach	Jurassic	Fresh
Richards Bay	Pt Durnford Fm muds, silts, F/sst	Sea cliff	Storm beach	Pleistocene	Semi-consolidated
Tofo, Mozambique	Tufa (no base seen)	Massive	Storm beach	Pleistocene	Tufa
³ Giants Causeway, N. Ireland	Basalt	Columnar basalt	Storm beach	Cretaceous	Fresh
St John's Point, N. Ireland	Limestone	n/r	Storm beach	Lower Carboniferous	Fresh
Luskentyre Bay (North), Harris Island, UK	Granitic	Deformed	Storm beach	Proterozoic–Archean	Fresh
Luskentyre Bay (South), Harris Island, UK	Granitic	Deformed	Storm beach	Proterozoic–Archean	Fresh
Northton, Harris Island, UK	Granitic	Sea cliff	N	Archean	Fresh
⁴ Kuwait Bay, Kuwait	Beach rock	Bedded	Not present	Late Quaternary	Fresh
⁵ SW.Australia	Limestone/granite	n/r	Storm beach	Pleistocene limestone/ granite (540–780 Ma)	Fresh
Monkey Mia, W. Australia	Not known	n/r	Not present	n/r	Fresh

¹ Perissinotto et al. (2014), ² Smith and Uken (2003), ³ Cooper et al. (2013), ⁴ Alshuaibi et al. (2015), ⁵ Forbes et al. (2010).

wards et al., 2017), and the north coast of Luskentyre Bay (Harris, UK). This stromatolite type appears to be restricted to clastic environments associated with the shore platform system and are therefore still termed SPS. Trapped and bound stromatolites are found growing on cemented beach gravel in breaks and gullies in the shore platform and beaches adjacent to the shore platform. The size of beach grain involved varies from fine sand to boulders. A storm beach deposit (6–10 cm thick) bound between two mineralised laminar stromatolites has been observed (Fig. 3b) (Smith et al., 2011). In addition, within a depression in the Cape Morgan shore platform, a headland conglomerate formed by stromatolite cementation of dolerite boulders is present (Smith et al., 2005); some of these boulders have been disaggregated and re-cemented into the conglomerate (Fig. 3c). Trapped and bound stromatolites are also known to be associated with strong terrestrial runoff.

3.3 Mineral precipitated stromatolites

Mineral precipitated stromatolites (which generally lack trapped and bound material) dominate the SPS facies association (Table 2; Fig. 1). SPS grow on shore platforms, within chemically – or mechanically – produced pools and barrage pools (see: Forbes et al., 2010), constructed by stromatolite growth and the inclined apron terrace slopes that connect them (Fig. 4b) (Campbell et al., 2015). The water in these shore platform pools is known to vary from fresh to hypersaline (Smith et al., 2011; Perissinotto et al., 2014) depending on immediate wave and weather conditions. Elevated water temperatures, as much as 10 °C above ambient environmental, at Cape Morgan, Luphatana and Richards Bay suggest inputs from warm thermal spring activity (Smith et al., 2011). These warm waters often occur at the base of pools, separated from the overlying water by a thermocline; in such cases, SPS growth is absent below the thermocline

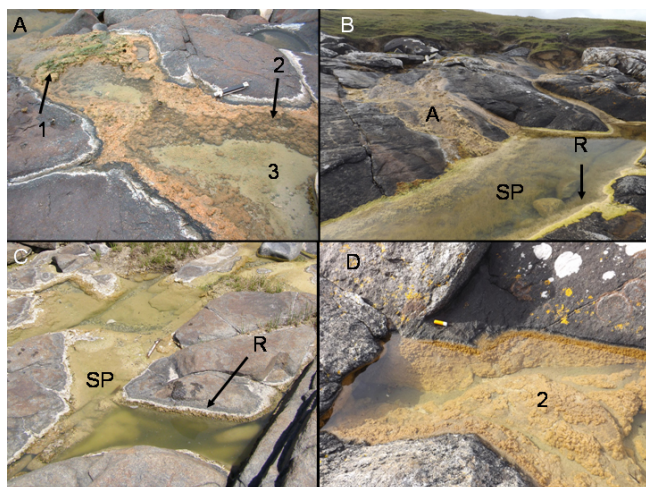


Figure 4. SPS mineral precipitated stromatolites. (a) Stromatolite pool showing: pustular (1), laminar and columnar (2), and colloform (3) stromatolite types from Cape Morgan, South Africa. (b) Stromatolite pool (SP), stromatolite apron (A), and stromatolite rim (R). (c) Joint controlled stromatolite pool (SP) and stromatolites, and a stromatolite rim (R). Both (b) and (c) are from Luskentyre Bay, Harris, UK. (d) Stromatolite pool from Mtentu, South Africa.

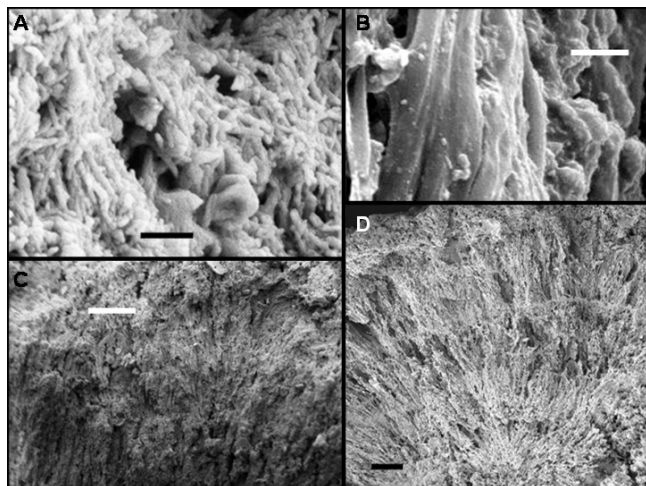


Figure 5. (a) High-magnification SEM image of stromatolite from Tofo (scale bar is 1 µm); (b) growing cyanobacteria filaments from Morgans Bay microbialite (scale bar is 10 µm); (c) calcified cyanobacteria filaments from Ballito (scale bar is 40 µm) and (d) domical calcified stromatolite from Morgans Bay (scale bar is 400 µm).

(Smith and Uken, 2003). At Cape Morgan and Tinley Manor, stromatolite colonies are clearly being fed by springs that emanate from a storm swash terrace, whereas at Luskentyre Bay, the colonies are fed from seeps flowing out of a peat bog (Fig. 6d). Water ponding within suitable topography on shore platform surfaces provides accommodation space for

growing SPS. SPS are variously present as thin crusts (1–30 cm thick), barrage deposits (Perissinotto et al., 2014), low mounds (> 20 cm high), and as oncoid-like cobble and boulder coatings (Edwards et al., 2017). These cobbles and boulders are probably the grinders involved in pothole production.

SPS growth zones are related to water physicochemistry, calcification, and limited to salinity values of < 20 psu (generally 2–10 psu) (Smith et al., 2011; Perissinotto et al., 2014; Edwards et al., 2017). In areas where groundwater discharge is very strong coralline red algae may alternate with tufa growth in the lower part of cliffs reaching down into the lower intertidal zone. SPS may therefore cease growing, desiccate, and suffer rain dissolution, and then regrow forming erosion surfaces. Growth cessation may be due to “self” blocking of the water conduit by stromatolite growth and carbonate precipitation, wave erosion, or drought conditions interrupting groundwater inflow.

Three depth-controlled, stromatolite morphologies have been reported from pools (Fig. 4a) (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016; Edwards et al., 2017). Partially emergent pustular stromatolites occur in the subareal wet area around pools and seeps (Fig. 4). This morphology occurs as mounds up to a few centimetres above pool rims and in very shallow water. At some localities (e.g. Lufatana and Mtentu: Fig. 1) the pustular stromatolite variety is not present. In these cases water inflow is via joint planes directly into the pools. Pustular stromatolite morphology is often a link morphology between stromatolites and tufa (Fig. 4a). Laminar and columnar stromatolites (1–10 cm high) occur in shallow water (Fig. 4a). This stromatolite morphology forms a pool rim at, and just below, the water surface (Smith et al., 2011; Edwards et al., 2017). Laminar stromatolite morphology is particularly common in the wind-shadow margins of pools, whereas in deeper pools (20–30 cm depth) only the colloform stromatolite morphology is present (Fig. 4a). SPS are highly colourful during bloom (Fig. 3), but become white on desiccation to a micrite crust.

The mineral precipitated SPS generally lack the particles that are present within the trapped and bound SPS (Fig. 5). The mineral precipitated SPS variation are characterised by a laminae comprising radiating cyanobacterial filaments, alternating with thinner concentric lamina (Fig. 5c, d). Radial SPS lamination is on a centimetre scale, whereas the concentric lamination is much thinner (Fig. 5b). Mineral precipitated stromatolites may contain trapped and bound material but this is rare. This suggests that the SPS trapped and bound and mineral precipitated stromatolites are end members of a continuous spectrum.

3.4 Tufa

Tufa waterfalls (see Perissinotto et al., 2014); varying from a few centimetres to several metres high, often coat cliffs and steep rock surfaces (Table 1; Fig. 3a, b). Tufa dominates



Figure 6. (a) Sandstone shore platform and boulder ridge at Luphatana, South Africa. Stromatolites are growing in the pool (see black arrow); 80 t boulders are present in the boulder ridge showing the contrasting shore platform environmental extremes. (b) Tofo, Mozambique, tufa shore platform with scattered large boulders. (c) Giant's Causeway basalt shore platform and cliffs. (d) Lewisian gneiss shore platform at Luskentyre Bay, Harris, UK – Note the peat marsh (P).

on coastlines characterised by sea cliffs (Table 2). At Cape Morgan an inter layering of tufa and coralline red algae was noted in the lower part of the intertidal zone at a locality characterised by a strong water inflow. If only cliffs are present (and no shore platform) only tufa is present. Tufa waterfalls are also often connected to SPS pools, either directly at the tufa toe or via connecting apron terraces.

4 Geomorphology and geology of SPS settings

All locations discussed are open coast except for Luskentyre Bay and Kuwait Bay (Table 2). The geomorphology of each shore platform is controlled by lithology, jointing, and bedding style. Shore platforms comprised a variety of competent lithologies (Table 2). Shore platforms vary from 5–60 m wide and are generally backed by a boulder beach or boulder ridge (Fig. 6). The boulder ridges contain angular blocks or megaclasts (up to 80 t), as opposed to the smaller (> 50 cm diameter) rounded boulders found in boulder beaches and gullies in, and adjacent to, the shore platform (Table 2).

Where the coast comprises incompetent lithologies no shore platforms can form. Competent sandstones form wide shore platforms (Fig. 6; Table 2). The SPS bearing shore platforms at Mtentu and Luphatana (Fig. 6c; Table 2) are formed in well-indurated Lower Devonian Msikaba Formation sandstone. These are the widest at up to 60 m wide. The Msikaba Formation is well-bedded (more-or-less horizontal) and vertically jointed. The shore platform has been formed by wave quarrying of large blocks, which break along bedding

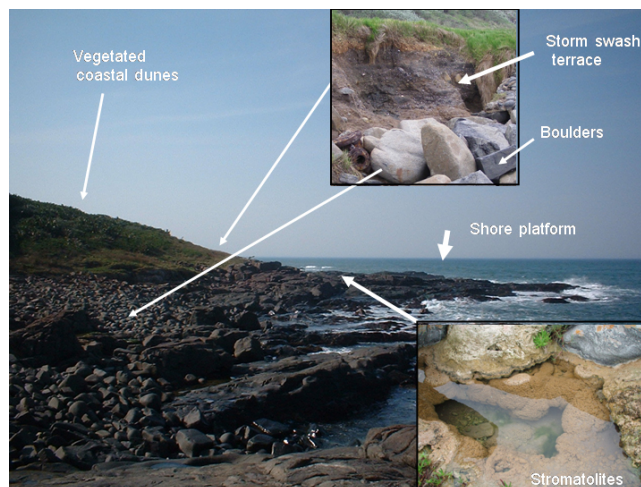


Figure 7. SPS facies association model based around the Cape Morgan SPS context.

and joint planes. The eroded boulders have accumulated in a boulder ridge at the rear of the platform (Fig. 6a).

At Cape Point SPS occurrences are rare but massive tufa deposits are present inland. Tufa is the main lithological component at Tofo, in comparison, and the shore platform has been excavated into this lithology (Fig. 6b), with thin (1–2 cm thick) sub-fossil stromatolites interbedded (Table 2). Sub-fossil mineral precipitated stromatolites are also found as upper intertidal and supra tidal active pothole linings. No growing tufa or stromatolites were observed, but the presence of SPS in potholes within an active shore platform indicates them to be recent. It is possible that this tufa deposit is related to a lower sea level stillstand and has been reworked into a shore platform where SPS has developed at a later stage.

Dolerite sill shore platforms are present at Tinley Manor, Ballito, and Cape Morgan (Fig. 1); the latter (Fig. 7) being the best example (Table 2). The dolerite is strongly jointed and forms a rugged shore platform, which tends to undulate and shows minor sea cliffs and pools. The sea cliffs are produced by wave bore quarrying of blocks along joint surfaces. Pools, in comparison, are formed by mechanical joint widening, pot holing, and chemical weathering, while barrage pools are impounded by stromatolite growth (Fig. 4).

At Port Edward (Fig. 1) granite forms a poorly developed shore platform littered with megaclasts. Minor SPS and tufa were noted near the landward shore platform boundary. The Luskentyre Bay, Harris Island, Scottish Hebrides (Fig. 1) granitic shore platform is backed by an extensive but thin (± 30 cm) peat bog. Seaward of this shore platform is a very extensive intertidal fine-grained low-end macrotidal flat (Fig. 6).

At Richards Bay (Fig. 1) the south-east African coastline is marked by the semi-indurated Pleistocene Port Durnford beds (Fig. 1), which comprise incompetent muds, silts and fine sands. The shore platform is poorly developed and

Table 3. Hinterland geology and geomorphology of SPS locations (gaps indicate not recorded).

Location	Shore platform	Cliff	Storm swash terrace	Dunes	Peat bog	Tufa	Urbanised
Cape Point, SA	Y	Y	N	N	n/r	Y	N
¹ Storms River	Y	n/r	n/r	n/r	n/r		N
¹ Oyster Bay	Y	N	n/r	Y	n/r		Partly
¹ Cape St Francis	Y	N	n/r	Y	n/r		Y
¹ Seaview	Y	N	n/r	Y	n/r		Y
¹ Skoenmakerskop	Y	N	n/r	Y	n/r		N
¹ Cape Recife	Y	N	n/r	Y	n/r		N
² Cape Morgan	Y	Y	Y	Y	Y		N
Luphatana	Y	N	Y	Y	Y		N
Mtentu	Y	N	Y	Y	Y		N
Port Edward	Y	N	Y	Y	Y		N
Ballito	Y	Minor	Y	N	Y		Y
Tinley Manor	Y	Minor	Y	N	Y		Y
Richards Bay	N	Y	N	Y	N		N
Tofo, Mozambique	Y	Y	N	Y	N		Y
³ Giant's Causeway, N. Ireland	Y	Y	Y	N	N		Some infrastructure
St John's Point, N. Ireland	Y	Y	n/r	n/r	N		N
Luskentyre Bay (S)	Y	Y	N	N	Y		N
Harris, UK							
Luskentyre Bay (N)	Y	N	N	N	Y		N
Harris, UK							
Northton	N	Y	N	N	Y		N
Harris, UK							
⁴ Kuwait Bay, Kuwait	Y	N	n/r	Y	N		N
⁵ N. Sea, Netherlands	N	N	n/r	n/r	N		N
⁶ SW Australia	Y	Y	n/r	n/r	n/r		N
Monkey Mia, W. Australia	Y	N	n/r	Y	N		N

¹ Perissinotto et al. (2014), ² Smith and Uken (2003), ³ Cooper et al. (2013), ⁴ Alshuaibi et al. (2015), ⁵ Kremer et al. (2008), and ⁶ Forbes et al. (2010).

backed by a retreating coastal cliff made up of the poorly consolidated Port Durnford Beds sediments. Only tufa is present growing on the cliff face but will not be preserved due to ongoing marine action.

5 SPS hinterland

Storm swash terrace deposits (McKenna et al., 2012; Dixon et al., 2015) occur at the rear of the Port Edward, Ballito, Tinley Manor, Mtentu, Luphatana, and Cape Morgan shore platforms. These are associated with boulder ridges, boulder beaches, and coastal dunes. Storm swash terrace deposits (McKenna et al., 2012) may partially bury older beach ridges. Boulder beaches are present at the Luskentyre Bay, Harris, Scottish Hebrides (UK), SPS sites but here the hinterland is characterised by peat bog overlying bedrock which projects through at high points (Fig. 6). At Tofo (Mozambique) the tufa is backed by a very extensive (kilometres wide) coastal dune cordon, which is strongly impacted by farming and urbanisation. Several SPS localities

have a coastal dune cordon hinterland and some are associated with bogs (Table 3). The hinterland at Giant's Causeway comprises high basalt cliffs (Fig. 6). A model of the SPS facies association is shown in Fig. 7.

6 Regional and global aspects

SPS occur in a variety of climatic and oceanographic settings (Table 4) and although no systematic survey of SPS distribution has yet been undertaken, we expect that they are globally widespread. Shore platforms, associated with boulder ridges and boulder beaches, are indicative of high wave activity (Hall et al., 2006; McKenna et al., 2012; Dixon et al., 2015). In the case of the southern African eastern seaboard this is confirmed by modally high wave conditions (Guastella and Rossouw, 2012). Extreme waves, however, exceed modal conditions by several metres. On the southern African eastern seaboard, extreme waves may originate from extratropical low pressure systems, tropical storms/ cyclones (Smith et al., 2010), and tsunamis can also not be ruled out.

Table 4. Tectonic and oceanographic aspects of SPS localities. Tidal data from the South African Naval Hydrographic Office and British Admiralty (measured values ^a; Sea level rise ^a, and Sea surface temperature ^b) and satides.co.za (modelled data)(n/g: not gauged).

Location	Tectonic	^a SLR (mm yr ⁻¹)	^b SST range (°C)	Tidal range (M)	Wave regime	Climate zone
Cape Point	Passive	1.94 (Simon's Town)	8–15	1.83*	Very high	Mediterranean
¹ Storms River	Passive	n/g	15.5–19.5	2.14	Very high	Moderate coast
¹ Oyster Bay	Passive	n/g	16–18	2.12	Very high	Moderate coast
¹ Cape St Francis	Passive	n/g	16–20.5	2.1	Very high	Moderate coast
¹ Seaview	Passive	n/g	16–20	n/g	Very high	Moderate coast
¹ Skoenmakerskop	Passive	n/g	16–23	n/g	Very high	Moderate coast
¹ Cape Recife	Passive	2.39 (PE)	16–23	1.99*	Very high	Subtropical coast
² Cape Morgan	Passive	n/g	17.5–20.5	1.98	Very high	Subtropical coast
Luphatana	Passive	n/g	19–22.5	n/g	Very high	Subtropical coast
Mtentu	Passive	n/g	19–22.5	n/g	Very high	Subtropical coast
Port Edward	Passive	n/g	19.5–23	2.05	Very high	Subtropical coast
Ballito	Passive	1.23 (Durban)	20.5–24.5	2.13*	Very high	Subtropical coast
Tinley Manor	Passive	n/g	20.5–24.5	n/g	Very high	Subtropical coast
Richards Bay	Passive	n/g	20–24.5	2.3	Very high	Subtropical coast
Tofo	Passive	n/g	22–29	5.0	Very high	Tropical coast
³ Giant's Causeway	Epeirogenic	0.07 (Dublin)	7.9–15.3	2.4* (Port Rush)	High	Cool temperate
St John's Point	Epeirogenic	0.07 (Dublin)	7.4–15.4	2.4* (Port Rush)	High	Cool temperate
Luskentyre Bay (S)	Epeirogenic	1.92 (Stornoway)		4.4* (Tarbert)	Moderate	Cool temperate
Luskentyre Bay (N)	Epeirogenic	1.92 (Stornoway)		4.4* (Tarbert)	Moderate	Cool temperate
Northton	Epeirogenic	1.92 (Stornoway)		4.4* (Tarbert)	Very high	Cool temperate
⁴ Kuwait	Epeirogenic	NA	13.3–32.3	4.3* (Kuwait Bay)	Low	Dry desert
⁵ SW Australia	Passive	1.54 (Fremantle)		NA	NA	Mediterranean
Monkey Mia, W. Australia	Epeirogenic	2.89 (Carnarvon)		NA	NA	Dry desert
⁶ N. Sea, Netherlands	Epeirogenic	1.71–2.53 (Netherlands)		NA	NA	Cool temperate

NA = not available

¹ Perissinotto et al. (2014), ² Smith and Uken (2003), ³ Cooper et al. (2013), ⁴ Alshuaibi et al. (2015), ⁵ Forbes et al. (2010), ⁶ Kremer et al. (2008). Sea surface temperature data obtained from Smit et al. (2013) for South Africa and Alshuaibi et al. (2015) for Kuwait.

A high swell event on 18–20 March 2007 (impacts ranged from Port Elizabeth to Maputo) (Fig. 1), was produced by a cut-off low pressure system. This event produced swells up to 14 m high ($H_s = 8.5$ m) with run-ups of 7–11 m (a.m.s.l.). (Smith et al., 2007). A further high swell event between 31 August and the 1st September 2008 impacted the southern and south-east African coast, from Cape Point to Cape Morgan (Fig. 1). This was generated by an extremely deep low pressure system and produced swells of $H_s = 10.7$ m (Guastella and Rossouw, 2012) with a 7–8 m run-up at Cape Morgan (Smith et al., 2014).

Field inspection following both the March (2007) and September (2008) high swell events indicated changes to the

Cape Morgan colonies (the other colonies listed in Table 1 were unknown prior to 2007). In the case of both storms, growing and unconsolidated microbial mat and large blocks of tufa were largely removed by wave action, but lithified stromatolites remained on the shore platform. Following the March 2007 event, surface stromatolite growth at Cape Morgan had been largely restored by January 2008.

At Ballito (Fig. 1), sub-fossil peritidal stromatolites that had been buried under coastal reclamation were exposed by erosion during the same 2007 high swell event. This event deposited a boulder beach (boulders > 1 m diameter) over the dolerite sill shore platform. At one point a thin crust of sub-fossil stromatolites was observed, which extended landward

under the boulder beach and storm swash terrace. This shows that SPS can be interbedded with storm deposits. At Cape Morgan, boulders on the boulder beach are often coated by stromatolite growth indicating periods of disaggregation and stability. Several rounded boulders were found with multiple rims of stromatolite, indicating they had experienced several cycles of stability and movement.

At Luphatana an extant SPS colony is located just in front of a boulder ridge which contains 80 t boulders, indicative of extreme waves (date unknown), the parameters of which are as yet unquantified (Fig. 5a). Similarly the St Johns Point and Giant's Causeway stromatolites (Cooper et al., 2013) are both associated with very large boulders. Wave spray deposits have been found at levels of 60 m (a.m.s.l.) at Cape Morgan, South Africa (Smith et al., 2014), whilst at Aird Uig (Harris, Scotland) wave scouring has taken place on a cliff top at a height of 20–30 m OD (Hall et al., 2006), proving that SPS can withstand the present extremes in wave climate.

The Irish and Scottish coasts are known for strong wave action (Hall et al., 2006; O'Brien et al., 2013) as the 2013–2014 storm season proved (Wadey et al., 2015). Both Giant's Causeway (on the west coast) and Luskentyre Bay are afforded some protection, but the boulder storm beaches at both localities (Table 2) have shown themselves to be vulnerable to wave attack.

It must be restated that this sample is far from complete, representing only coastlines that have been investigated. From Table 4, however, the following about extant SPS can be noted:

- SPS have been recorded in passive plate margins and epeirogenic settings.
- They occur from microtidal to macrotidal environments.
- Colonies have been noted in regions with sea level rises varying from 0.07 to 2.89 mm yr⁻¹.
- SPS form in coastal areas with sea surface temperatures varying from 7.4 to 32.3°.
- Colonies have been found in cool temperate to dry desert regions.
- SPS colonies are found in areas with varying high wave regimes – all characterised by boulders.

7 Discussion

SPS grow in shore platform depressions on high-energy coasts, such as shallow rock pools (Smith et al., 2011; Perissinotto et al., 2014; Rishworth et al., 2016), potholes, and SPS dammed barrage pools (Forbes et al., 2010; Perissinotto et al., 2014). SPS comprise thin micritic crusts, with only rare examples of trapped and bound stromatolite

varieties being associated. Not all localities show the complete tripartite stromatolite morphology (Fig. 4a). The pustular variety may be absent but the subaqueous laminar and columnar and the colloform variety are ubiquitous. Where vertical surfaces are present tufa grows.

Any SPS model must take into account that they form at the interface of freshwater seeps and high energy rocky peritidal zones (Smith et al., 2011; Perissinotto et al., 2014). The SPS are calcium carbonate mineralised due to the high pH regime (Smith et al., 2011) and grow on older siliceous rocks (Tofo may be an exception but the base is not visible) within a siliciclastic contemporary setting. Mud and sand pass through this system but are not deposited in significant amounts. Microbialites are ubiquitous in the peritidal setting but only become stromatolites if a carbonate rich groundwater plume is present (Smith et al., 2011; Rishworth et al., 2016).

The following points also need to be considered, although they may, or may not, be necessary for SPS growth. Sea level rise is ongoing. SPS possess seasonal to sub-seasonal (due to storm abrasion) laminae (Smith et al., 2005). The lack of climax lamination (Reid et al., 2000), characterised by diatoms (Smith et al., 2005) in the calcified form may be due to storm activity or non-calcification of this lamina type. Warm thermal groundwater may be present indicating a groundwater source. The stromatolites and shore platform contact is an unconformity.

The diversity of shore platform substrates suggests that lithology is not important for SPS growth; however, the competency of the substrate is vital for growth and probably for potential preservation. Tufa deposits and pustular stromatolite deposits are very unlikely to survive transgression or regression as there is no accommodation space. However, SPS in rock pools and barrage pool build-ups can form lenses or layers of stromatolite which could then be overstepped during marine transgression (possibly similar to the multi-metre steps which post-dated the last glacial maximum) and preserved in a future stratigraphy. Marine processes may break up the stromatolites and free stromatolite encrusted boulders from barrage and rock pools, such as is seen at Cape Morgan (Fig. 2a), and transport them as littoral drift for deposition elsewhere as conglomerates. Sea level rise (SLR) is taking place globally, thus SPS deposits could form as part of a global transgressive coastal sequence.

The best opportunity for preservation is provided by rock pools, especially potholes, in competent shore platform rock as this provides accommodation space. SPS growth itself could seal the SPS deposit, especially in flat bedded competent sandstone as at Mtentu and Luphatana (Fig. 5). Thus SPS environments could be preserved as lenses on palaeo-shore platforms. The extant stromatolite regrowth seen at Ballito (Fig. 1) suggests that preservation can take place. An investigation of subaqueous post-last glacial maximum coastlines might resolve this issue.

Table 5. Comparison of SPS with some Precambrian stromatolites.

Rock unit	Age (Ga)	Energy	Palaeo-tidal regime	Coast	Palaeo-substrate	Transgression	Source
Isua Group Greenland	3.7	NA	Shallow marine	Soft?	Metacarbonate	NA	Nutman et al. (2016)
Strelley Pool Chert, N. Aus	3.43	Hi	Peritidal	Rocky (SPS)	Jasper banded black chert; potholes	Transgression	Allwood et al. (2006)
Josefsdal Chert, SA	3.5–3.3	Hi	Peritidal	Soft?	Volcanic sedts/ Hydrothermal spring source	NA	Westall et al. (2006)
Moodies Group, SA	3.22	Med	Inter to subtidal	Soft (gravel)	Sand	Transgression	Gamper et al. (2011), Ericksson et al. (2006)
Pongola Group, SA	2.9	Low	Inter-to-subtidal	Soft?	Sand	Transgression?	Mason and Von Bruun (1979), Bolhar et al. (2015)
Malmani Dolomite, SA	2.56–2.52	Low-Hi	Peritidal to deep subtidal-	Soft?	Variable	Transgression?	Summer and Grotzinger (2004)
Turee Creek Group, W. Australia?	2.45–2.22 Ga	Hi	Sub-tidal	Soft?	Sandy siliciclastic/carbonate	Progradation	Martindale et al. (2015)
Gunflint chert, Canada	1.88				Archean lava with rounded boulders	Transgression	Brasier et al. (2015)
Extant SPS	Extant	Very Hi	Peritidal	Rocky (SPS) and T and B very rare)	Dolerite, sandstone, tufa granite sand and gravel (very rare)	Transgression	Smith and Uken (2003), Perisotimo et al. (2014), This study

NA = information is not available

7.1 Global extant stromatolites

There are several important differences between the extant SPS described here and other, well known extant stromatolite occurrences. Variations on the Hamelin Pool theme are generally used for artists' conceptions of the Archean; however this instance is unusual as within a hypersaline lagoon (Logan et al., 1964). The Highborne Cay, Bahamas sub-tidal model is characterised by columnar stromatolites within an ooid shoal (Reid et al., 1995; Visscher et al., 1998; Baumgartner et al., 2009). Both Shark Bay and the Bahamian extant stromatolite settings contain stromatolites produced by trapping and binding within a soft coastline. These may leave traces such as microbially induced sedimentary structures (MISS) (Noffke and Awramik, 2013) but are unlikely to be preserved in the long term. Kremer et al. (2008) found calcium carbonate being precipitated within annual Cyanobacteria mats at beaches on the Dutch North Sea, but again these were of the trapped and bound variety, as opposed to mineral precipitation. The Kuwait Bay examples (Alshuaibi et al., 2015), however, are of the mineral precipitation variety; these are developed on beach rock and could conceivably be preserved.

7.2 Precambrian stromatolites

Precambrian stromatolites are commonly found to have developed in transgressive settings on varying substrate types (Table 5). Erosion surfaces are common within them (Van Kranendonke, 2011; Nutman et al., 2016) as is the case with SPS. In the case of Strelley Pool (Australia), stromatolites initially formed on a rocky shore platform (Allwood et al., 2006), which compares well with SPS (Tables 1 and 2). Allwood et al. (2006) base this interpretation on the following:

1. Wide and discontinuous distribution of boulders with a rounded clast-supported fabric.
2. Correlation between clast and substrate, on an unconformity.
3. Substrate-dependent lateral transition from clustered and isolated large boulders on a shore platform to embayment beach conglomerates type.
4. The presence of palaeo-cliffs, fissures, and cavities in the substrate.
5. Soft mud intraclasts and desiccation cracks associated with local mudstone substrate.

The extant SPS facies association demonstrates all the points made by Allwood et al. (2006) concerning the Strelley Pool stromatolites (Tables 1 and 2); the stromatolite morphological scale of the two is also similar. Although the SPS horizontal exposures vary from 10 to 100 s of metres, they are time equivalents and, if conditions where right, could

develop into beds stretching for 10 or 100 s of kilometres. The presence of "stromatolites" on vertical surfaces at Strelley Pool is interesting as this suggests that they were associated with tufa. This, in turn, shows that tufa can be preserved despite the perceived lack of accommodation space. The 1.88 Ga Gunflint Chert is based on a weathered Archean lava, characterised by rounded lava boulders (Brasier et al., 2015) and may also be a palaeo-SPS occurrence.

In contrast to SPS most Precambrian stromatolites apparently formed on soft coastlines (Table 5). Perhaps the Precambrian marine climate was markedly less aggressive than at present or stromatolites were simply preserved in low energy embayments such as Kuwait Bay (Alshuaibi et al., 2015) or Luskentyre Bay.

The presence of tufa within the SPS facies association and its similarity to that of the 3.4 Ga Strelley Pool stromatolites strongly hints that microbial life existed in Archean terrestrial settings. It is quite reasonable to assume that tufa was present landward of Archean stromatolite settings, but was not preserved.

7.3 SPS as a modern Precambrian analogue

It has been suggested that no adequate marine extant stromatolite analogue exists for Precambrian marine mineral precipitated stromatolites, as most modern marine extant stromatolites are of the trapped and bound variety (Awramik and Grey, 2005). However, the mineral precipitated SPS deposits fill this gap. Most Precambrian stromatolites formed in a transgressive setting, similar to the SPS (Table 5). The peritidal stromatolite setting is a common theme for Precambrian stromatolites; although intertidal and subtidal components are also present (Table 5). The SPS setting shows only a stunted intertidal and no subtidal component. Microbialite develops in the crack between terrestrial and marine influence where metazoans are reduced by the extreme nature of this setting, and thus competition for space is reduced. If the groundwater chemistry is suitable, SPS form. It is easy to imagine how the SPS environment would unfold if metazoan activity was reduced or not present, as was the case in the Precambrian; this would allow large subtidal stromatolites, such as those in the Malmani Dolomite (Sumner and Grotzinger, 2004) (Table 5) to develop. Similarly it is very likely that tufa existed in the terrestrial environment, but has not been preserved (or recognised). The SPS model strongly suggests the occurrence of terrestrial prokaryotes during the Archean. Extant SPS are growing during a mild transgression, thus their preservability at present is probably low. However, should SLR accelerate in the future, it is possible that this environment could be overstepped and preserved as rock pool and pothole fills. The lower colloform and laminar stromatolite variety are more likely to be preserved and the tufa least likely or not at all.

7.4 Extraterrestrial implications

Phosphorous on Mars is more common than on Earth (Greenwood et al., 2007) so it is possible that simple Martian life may have been present. If this was the case, and the water chemistry was suitable, then stromatolites could have formed. Marine and lacustrine flooding surfaces on Mars should be consequently be investigated. Palaeo-shore platforms, especially if associated with megaclast fields or ridges, should be targets for investigation. Although no shore platforms have been reported (Banfield et al., 2015) as yet, the terrain at Chryse Planitia and Arabia Terra, which border the postulated Vastitas Borealis Ocean (Wilson et al., 2016; Rodriguez et al., 2016), could be shore platform candidates. Recently Ruff and Farmer (2016) suggested that structures in the Ma'Adim terraces within the Gusev Crater are siliceous stromatolites. These terraces may have been formed by wave action in the Gusev Palaeolake or at the margin of the Vastitas Borealis Ocean and may be an extraterrestrial palaeo-SPS environment.

8 Conclusions

Extant SPS are present on high energy rocky coasts, on passive margins, and in epeirogenic settings; however this may be a function of sampling. They are associated with well-indurated shore platforms, boulder ridges, and boulder beaches. The hinterland is frequently boggy or marshy. SPS appear to be unrelated to climate and tidal regime, but they may be better developed in warmer climates but the sample size is currently too small to confirm this. If vertical surfaces are present on the shore platform, tufa forms. In shallow shore platform pools SPS develop. There is a gradation from SPS to tufa. SPS develop within transgressive settings, as was the case with many Precambrian stromatolites. The preservability of these micrite stromatolites is probably low, but may improve with stromatolite cementation to competent substrate rock. Contemporary rocky and Quaternary coastlines should be investigated globally for the SPS environment. The SPS setting is a valid analogue for the Archean Strelley Pool stromatolite and possibly the base of the Gunflint stromatolite occurrence; however, most Precambrian stromatolites appear to have formed on soft coastlines. The association with trapped and bound stromatolites and the Luskentyre Bay environment (shore platform and tidal flat) hints at a possible SPS soft coastline link. Finally, shore platform settings should be targets in the search for Martian stromatolites.

Data availability. All the data used are presented in tables and images of this article.

Competing interests. The authors declare that they have no conflict of interest.

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